APPENDIX B

EXAMPLES OF CRACK ARRESTOR DESIGN PROCEDURES

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Examples of the crack arrestor design procedures for each of the basic arrestor designs (loose sleeves, tight sleeves, grouted sleeves, and toroidal) are presented in this appendix. In each example the general design procedures outlined in the Design Guidelines Section of this report are followed.

Example B.1: Loose Sleeve Sample Case

The pipeline design is a buried 42-inch-diameter by 0.700-inch thick X70 pipe operating at 1680 psig (72 percent SMYS). The pipe is to have a minimum full-size Charpy energy of 35 ft-lb and 100 percent shear area in a DWTT at the minimum service temperature. The pipeline will be used only for pure methane transportation, i.e., no heavy hydrocarbon additives. The desired loose sleeve radial clearance is 0.5 inch for ease of slipping on. The arrestor is to be made from an expanded piece of X60 pipe. What is the minimum arrestor length and required thickness?

Step 1 - Calculate Ductile Fracture Speed

Pure methane will decompress as a pure gas, and the gas decompression curve to determine the fracture speed is relatively simple to calculate. Here the wave velocity (V_w) is determined as a function of the decompressed pressure (P_d) by using Equation (B.1).

$$P_d = \left[P_i \quad \frac{2}{\gamma + 1} + \left(\frac{\gamma - 1}{\gamma + 1}\right) \frac{V_w}{V_{ai}}\right]^{\frac{2\ \gamma}{\gamma - 1}} \qquad (B.1)$$

For natural gas (pure methane) V_{ai} (the initial acoustic velocity) is 1300 feet per second, the specific heat ratio (γ) is 1.4, and in this case P_i = 1680 psig. Hence, Equation (B.1) simplifies to

$$P_d = 1680 \left[\frac{5}{6} + \frac{V_w}{6\ (1300)}\right]^7 \tag{B.2}$$

The decompression curve of P_d versus V_w is shown in Figure B.1.

To determine the fracture speed, Equation (B.3) is then used to determine the fracture speed as a function of the decompressed pressure. One can determine the fracture speed graphically from the intersection of the P_d versus V_f curve from Equation (B.3) (sometimes referred to as a J-curve because of its shape) and the decompression curve from Equation B.2.

$$V_f = \frac{C_1\ \bar{\sigma}}{\sqrt{\mathcal{R}}} \left(\frac{P_d}{P_a} - 1\right)^{C_3} \tag{B.3a}$$

$$P_a = \left[\frac{1000\ \bar{\sigma}\ t}{3.33\ R}\right] \left[\frac{2}{\pi}\right] \cos^{-1}\left\{\exp - \left[\frac{C_2\ \mathcal{R}}{(\bar{\sigma})^2 \sqrt{Rt}}\right]\right\} \tag{B.3b}$$

The symbols in Equation (B.3) are defined in the Background and Nomenclature Sections of the report.

For backfilled pipe the constants C_1, C_2, and C_3 are 47.7, 380, and 1/6, respectively. $\mathcal{R}$ is the full-size Charpy V-notch energy in ft-lb which is 35 ft-lb in this example. R is 21 inches and t is 0.70 inch. The flow stress, $\bar{\sigma}$, is the yield strength plus 10 ksi, which is 80 ksi in this example. Equations (B.3a) and (B.3b) therefore simplify to Equations (B.4a) and (B.4b).

$$V_f = \frac{47.7(80)}{\sqrt{35}} \left(\frac{P_d}{P_a} - 1\right)^{1/6} \tag{B.4a}$$

$$P_a = \left[\frac{(1000)(80)(0.7)}{(3.33)(21)}\right] \left[\frac{2}{\pi}\right] \cos^{-1}\left\{\exp - \left[\frac{(380)(35)}{(80)^2\sqrt{(21)(.7)}}\right]\right\} \tag{B.4b}$$

Equations (B.4a) and (B.4b) then simplify to Equation (B.5). A plot of V_f versus P_d (the J shaped curve) is shown in Figure B.1. along with the methane decompression curve. The intersection of the two

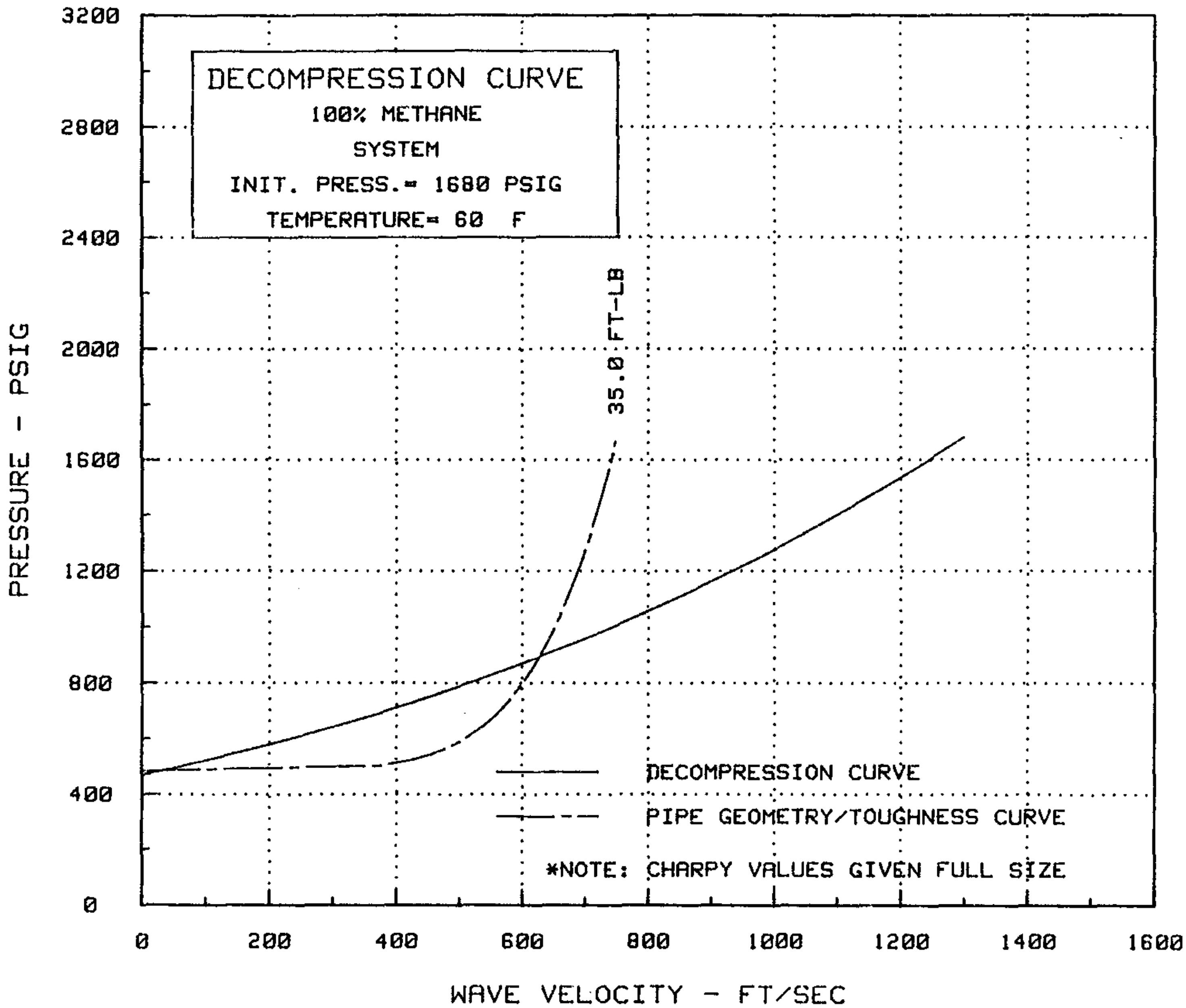

FIGURE B-1. DECOMPRESSION CURVE OF PURE METHANE AT 1680 PSIG AND J-CURVE FOR 42-INCH DIAMETER BY 0.700-INCH WALL X70 PIPE. (INTERSECTION OF THE TWO CURVES DETERMINES THE FRACTURE SPEED.)

curves determines the fracture speed. Other than using the graphical approach, one could also combine Equations (B.2) and (B.5) by substituting Equation (B.2) for P_d in Equation (B.5) and solving for V_f (by trial and error) where $V_f = V_w$.

$$V_f = 645 \left[\frac{P_d}{484} - 1\right]^{1/6} \quad \text{(B-5)}$$

As can be seen in Figure B.1, the calculated fracture speed is 627 fps.

Step 2 - Determine Radial Clearance

In this case the radial clearance was already specified as 0.5 inch. The normalized C_r/R is therefore (0.5/21) or 2.3 percent. (Note, the 0.5 inch is the clearance on the radius, not the total diameter clearance.)

Using the calculated fracture speed, V_f, for 627 fps and the normalized radial clearance C_r/R, of 2.3 percent, the axial length of the sleeve can be determined in two ways. The nondimensional sleeve length could be estimated from the graph in Figure 18. This requires some interpolation in this case. The axial sleeve length could also be calculated using the equations given below, which are the basis of the theoretical analysis method which produced the results in Figure 18.

$$V_f = M(L/D) + V_{min} \quad \text{(B.6a)}$$

$$V_{max} = 2000 - 31{,}800\,(C_r/R) \quad \text{(B.6b)}$$

where L/D = Axial length of sleeve divided by pipe diameter.

M = Slope of the arrest/propagate boundary which is given graphically in Figure B.2 as a function of radial clearance. Figure B.2 was produced from data used to generate Figure 14 and Figure 18.

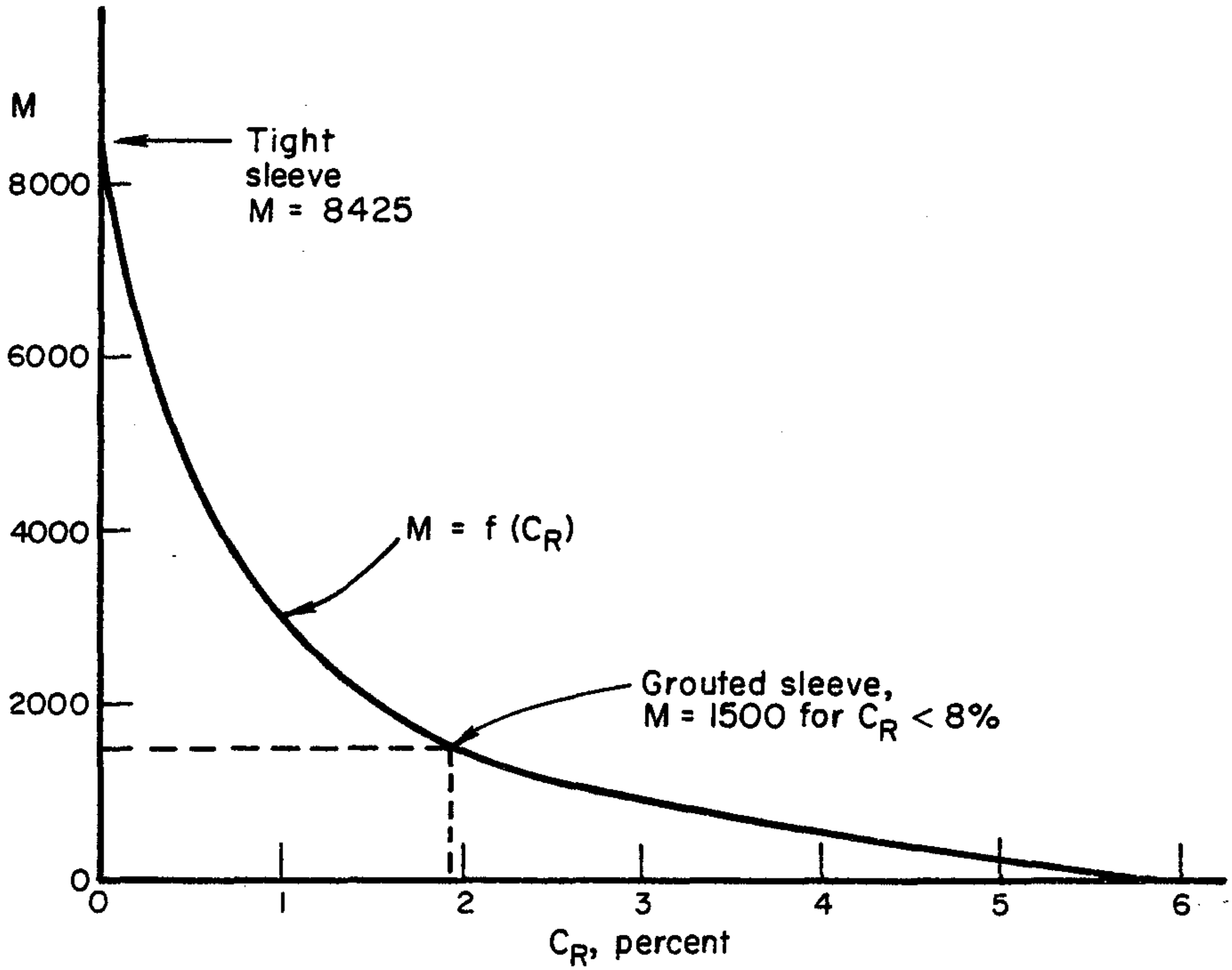

FIGURE B-2. SLOPE OF THE ARREST/PROPAGATE BOUNDARY LINES AS A FUNCTION OF RADIAL CLEARANCE FOR SLEEVE ARRESTORS

V_{min} = Minimum unstable ductile fracture speed, i.e., generally close to 250 fps. This can also be determined graphically where the J curve and decompression curves become tangent, see Figure 2 in the main body of the report.

V_f = Calculated fracture speed, however, V_f should never be greater than V_{max} in Equation (B.6b). If V_f is greater than V_{max}, then arrest with the selected radial clearance will not occur regardless of the sleeve length.

For this particular case C_r/R = 2.3 percent and V_{max} = 1268 fps. Thus the calculated fracture speed of 627 fps is less than V_{max}. Using V_{min} of 250 fps, V_f of 627 fps from Figure B.1, and M of 1150 from Figure B.2, then Equation (B.6a) becomes

$$627 = 1150\ (L/D) + 250 \tag{B.7a}$$

$$L/D = (627-250)/1150 = 0.33 \tag{B.7b}$$

$$L = 0.33D = 0.33(42) = 13.86 \text{ inches} \tag{B.7c}$$

Hence, L/D = 0.33 and the minimum axial sleeve length is 0.33 times the pipe diameter or approximately 13.9 inches.

Step 4 - Determine Arrestor Thickness

The arrestor thickness should be in proportion to the pipe thickness and the ultimate strengths of the pipe and arrestor, as per Equation (B.8a).

$$t_{arr} = t_{pipe} \left(\frac{\sigma_{u(pipe)}}{\sigma_{u(arr)}}\right) \tag{B.8a}$$

For this sample case Equation (B.8a) becomes

$$t_{arr} = (0.700)\left(\frac{82,000}{75,000}\right) = 0.760 \text{ inch} \qquad \text{(B.8b)}$$

where 82,000 and 75,000 are the specified minimum tensile strengths of X70 and X60, respectively according to API 5LX. The minimum thickness of the X60 arrestor material should be 0.760 inch.

Step 5 - Toughness Specification

As noted in the introduction to this section, a minimum toughness of 50 percent shear on a transverse Charpy specimen at the lowest expected service temperature would be a sufficient toughness. A more conservative specification would be to require 50 percent shear area on a full-thickness transverse DWTT specimen.

Step 6 - Select a Safety Margin

The calculated arrestor size from the preceding steps yields an arrestor that will just barely arrest a crack. Safety margins need to be added to the arrestor length or to its thickness.

For instance, if a fracture speed of 1000 fps were used to be conservative, then the minimum axial length of the sleeve would be 27.4 inches as illustrated in the calculations below.

$$V_f = M(L/D) + V_{min} \qquad \text{(B.9a)}$$

$$1000 = 1150\ (L/D) + 250 \qquad \text{(B.9b)}$$

$$L/D = 0.652 \qquad \text{(B.9c)}$$

$$L = (0.652)(42) = 27.39 \text{ inch} \qquad \text{(B.9d)}$$

Example B.2: Tight Sleeve Example Case

Tight sleeves are generally less desirable than loose or grouted sleeves because of the tendency of the propagating axial crack to tear around the circumference of the pipe which may cause the pipe to be lifted out of the ground. However, this case was chosen for illustrations of the general calculation procedures. For simplicity, here the sample case is the same as the above case.

Step 1 - Determine Fracture Speed

The fracture speed was calculated in the prior example and was found to be 627 fps.

Step 2 - Determine Radial Clearance

In this case the radial clearance is zero percent.

Step 3 - Determine Arrestor Length

For a tight sleeve the value of M for Equation (B.6a) is 8425, see Figure B.2. Hence, the arrestor length is determined from the calculations below.

$$V_f = M\ (L/D) + V_{min} \tag{B.10a}$$
$$627 = 8425\ (L/D) + 250 \tag{B.10b}$$
$$L/D = 0.045 \tag{B.10c}$$
$$L = (0.045)(42) = 1.89 \text{ inches} \tag{B.10d}$$

Recall that V_f must be less than V_{max}, otherwise the fracture could propagate under the arrestor, regardless of the arrestor length. In this case,

$$V_{max} = 2000 - 31{,}800\ (Cr/R) \tag{B.11a}$$

$$V_{max} = 2000 \text{ fps} \tag{B.11b}$$

Since the fracture speed is 627 fps, this design criterion is met.

Step 4 - Determine Arrestor Thickness

This was done in the previous example and was found to be 0.760 inch for X60 sleeve material.

Step 5 - Toughness Specification

This was done in the previous example. A minimum transverse full-size Charpy shear area of 50 percent, or a transverse DWTT shear area of 50 percent would be sufficient.

Step 6 - Select a Safety Margin

As previously noted the arrestor size calculated in the above steps is a marginal design. In this case we'll select a safety margin based on the assumption that some of the arrestors will not be tight, but could have a radial clearance of 1/8 inch. This is a C_r/R of approximately 0.6 percent. A fracture speed of 1000 fps will also be used as an additional safety margin.

For C_r/R = 0.6 percent, M in Figure B.2 is 4750. Hence, the tight sleeve arrestor axial length as determined below is 6.636 inches.

$$V_f = M(L/D) + V_{min} \tag{B.12a}$$

$$1000 = 4750\ (L/D) + 250 \tag{B.12b}$$

$$L/D = 0.158 \tag{B.12c}$$

$$L = (0.158)(42) = 6.636 \text{ inches} \tag{B.12d}$$

Example B.3: Grouted Sleeve Sample Case

The proposed pipeline system is 36-inch-diameter by 0.831-inch wall X65 pipe operating at 2160 psig (72 percent SMYS). The specified toughness of the pipe is 30 ft-lb transverse Charpy energy and a DWTT 85 percent shear area at 20 F below the minimum operating temperature. The pipeline is to carry liquid CO_2 at 70 F to 100 F. The impurities in the CO_2 are important in calculating the decompression curve which is used to determine the fracture speed. In this case, the impurities are limited to 2 percent nitrogen. A grouted sleeve arrestor using epoxy grouting with a radial clearance of 0.81 inch is selected. The sleeve will be made from X52 material.

Step 1 - Determine Fracture Speed

This step requires a graphical comparison of the decompression curve of the liquid CO_2 and the J curve of the pipe (Equations (B.13a) through (B.13f)). For liquid CO_2 the decompression goes from an all liquid into the two-phase region. As the liquid decompresses to the saturation pressure, there is a large change in the acoustic velocity, which keeps the pressure constant until a low wave velocity is reached. Such calculations require an equation of state computer program. Figure B.3 shows the calculated decompression curve for the liquid CO_2 at 100 F with 2-percent nitrogen.

The J curve for the pipe can then be calculated using the equations below.

$$P_a = \left(\frac{1000\ \bar{\sigma}\ t}{3.33\ R}\right) \frac{2}{\pi} \cos^{-1}\left\{\exp - \left(\frac{380\ \mathcal{R}}{\bar{\sigma}^2\ \ Rt}\right)\right\} \qquad \text{(B.13a)}$$

$$P_a = \left[\frac{(1000)(75)(.831)}{(3.33)(18)}\right] \frac{2}{\pi} \cos^{-1}\left\{\exp - \left[\left(\frac{(380)(30)}{(75)^2\ \ (18)(.831)}\right)\right]\right\}$$

(B.13b)

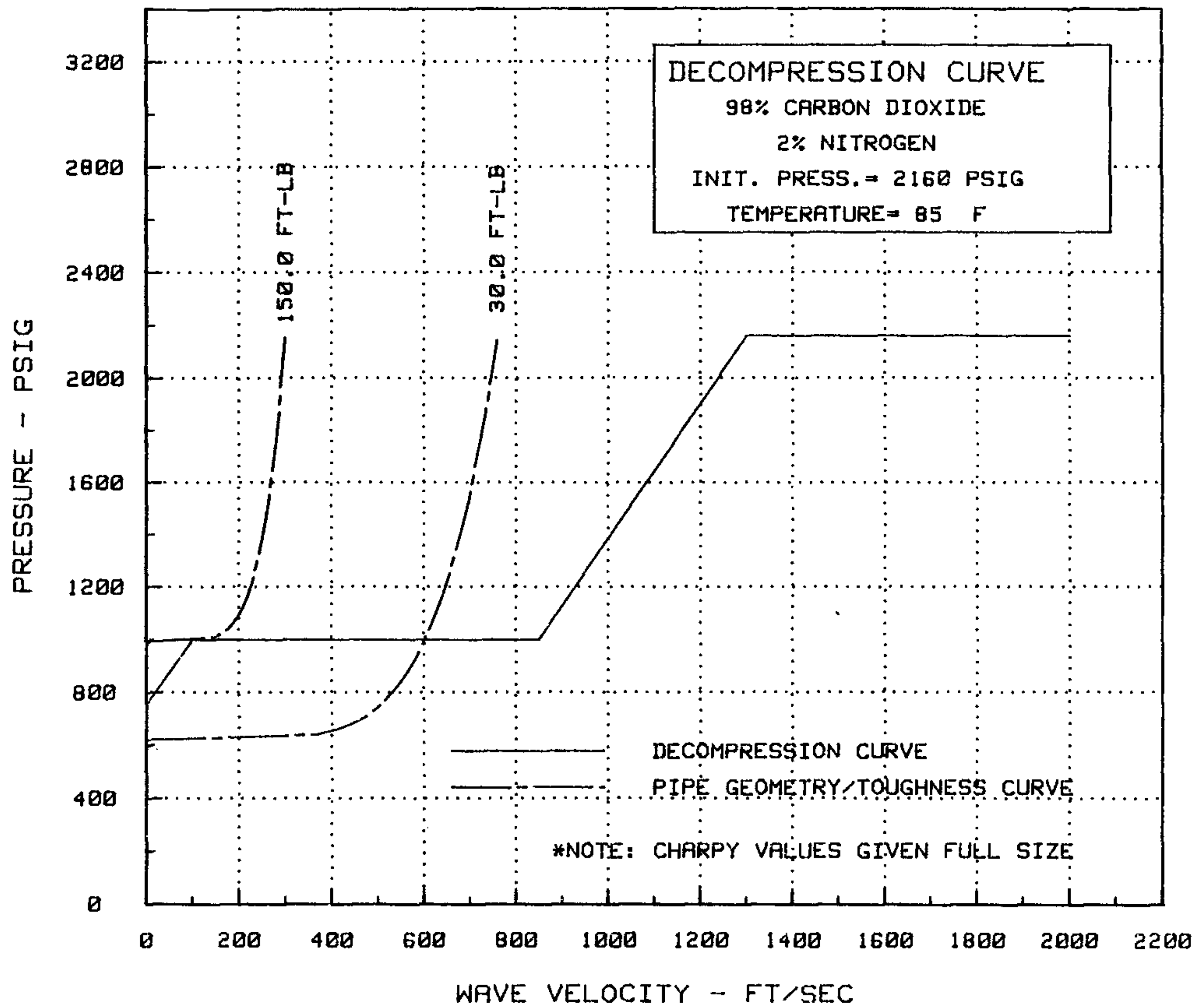

FIGURE B-3. DECOMPRESSION CURVE FOR LIQUID CO_2 AT 100 F WITH 2 PERCENT NITROGEN IMPURITIES AND J-CURVE FOR 36-INCH-DIAMETER BY 0.831-INCH WALL X65 PIPE. (PREDICTED FRACTURE SPEED IS 600 FPS.)

$$P_a = 620 \text{ psi} \tag{B.13c}$$

$$V_f = \frac{47.7\ \bar{\sigma}}{\sqrt{\mathcal{R}}} \left(\frac{P_d}{P_a} - 1\right)^{1/6} \tag{B.13d}$$

$$V_f = \frac{(47.7)(75)}{\sqrt{30}} \left(\frac{P_d}{620} - 1\right)^{1/6} \tag{B.13e}$$

$$V_f = 653 \left[\left(P_d/620\right) - 1\right]^{1/6} \tag{B.13f}$$

Figure B.3 shows the decompression curve and the J curve (Equation (B.11f)). The calculated fracture speed is 600 fps. Also note that for this case V_{min} is 175 fps, see Figure B.3.

Step 2 - Determine Radial Clearance

In this case the radial clearance has been specified as 0.81 inch. The normalized C_r/R is therefore (0.81/18.0) or 4.5 percent. However for grouted sleeves, the 1.9-percent radial clearance loose sleeve design curves have been shown to be appropriate.

Step 3 - Determine Arrestor Length

For grouted sleeves, the developed analysis shows* that for grouted radial clearances of less than 4.5 percent of the pipe radius, the grouted sleeves behave as a loose sleeve with a 1.9 percent radial clearance and the appropriate M value for Equation (B.14) is 1500.

$$V_f = M(L/D) + V_{min} \tag{B.14}$$

*Experiments on arrestors with up to 8 percent have been conducted and shown to be equivalent to loose sleeves with a 1.9 percent radial clearance.

For this particular decompression behavior V_{min} was determined to be 175 fps, which is much less than for natural gas decompression. The grouted sleeve length is then calculated to be 5.88 inches as shown in the equations below.

$$600 = 1500\ (L/D) + 175 \tag{B.15a}$$

$$L/D = 0.283 \tag{B.15b}$$

$$L = (0.283)\ (36) = 10.19 \text{ inches} \tag{B.15c}$$

The fracture speed must also be less than V_{max} if this arrestor is to work. As shown in the calculations below V_{max} is greater than the 600 fps fracture speed.

$$V_{max} = 2000 - 31{,}800\ (C_r/R) \tag{B.16a}$$

$$V_{max} = 2000 - 31{,}800\ (0.019) = 1396 \text{ fps} \tag{B.16b}$$

Step 4 - Determine Arrestor Thickness

In this case the arrestor material is X52 pipe. The minimum tensile strength for X52 according to API 5LX is 66 ksi, and for X65 it is 77 ksi. Hence, the arrestor thickness is calculated using the equations below.

$$t_{arr} = t_{pipe} \left(\frac{\sigma_{u(pipe)}}{\sigma_{u(arr)}} \right) \tag{B.17a}$$

$$t_{arr} = 0.831 \left(\frac{77.0}{66.0} \right) = 0.970 \text{ inch.} \tag{B.17b}$$

Step 5 - Toughness Specification

Since this is relatively heavy wall pipe, it is recommended to use a DWTT specification with a minimum shear area of 50 percent.

Step 6 - Select a Safety Margin

In this case a safety margin could be selected on the basis of the highest fracture velocity at the saturation pressure (1000 psig). From Figure B.3 this fracture speed is 900 fps. Using this fracture speed, the axial length of the grouted sleeve is determined below to be 17.40 inches.

$$900 = 1500(L/D) + 175 \tag{B.18a}$$
$$L/D = 0.483 \tag{B.18b}$$
$$L = 0.483(36) = 17.40 \text{ inches.} \tag{B.18c}$$

Another way of assessing the required safety margin is to calculate the required sleeve length assuming the grouting is accidently left out, or only the bottom of the annular space is grouted. For a calculated fracture speed of 600 fps and a 4.5 percent radial clearance, loose sleeve arrestor, M from Figure B.2 is 400. Hence, the calculated arrestor length would be 44.1 inches.

$$600 = 400(L/D) + 175 \tag{B.19a}$$
$$L/D = 1.063 \tag{B.19b}$$
$$L = 1.063(36) = 38.2 \text{ inches.} \tag{B.19c}$$

However, V_f must be less than V_{max} from Equation B.6b).

$$V_{max} = 2000 - 31,800\ (C_r/R) \tag{B.20a}$$
$$V_{max} = 2000 - 31,800\ (0.045) = 569 \text{ fps.} \tag{B.20b}$$

Since the calculated V_f of 600 fps is greater than V_{max}, an ungrouted 4.5 percent radial clearance sleeve of any length would not arrest a fracture. Therefore, extra precautions should be made to assure the arrestor is properly grouted.

Examples B.4: Toroidal Crack Arrestor Example Case

This example is for a double toroidal arrestor using the silo clamp style connector block as shown in Figure 6. The steps for installation of a silo clamp style connector block toroidal arrestor are illustrated in Figure 24. The hypothetical pipeline design factors are: 48-inch-diameter by 0.738-inch thick X65 pipe operating at 1440 psig (72 percent SMYS). The pressurized fluid is a rich gas at 25 F with the composition below.

87.35 methane
8.08 percent ethane
4.35 percent propane
0.22 percent IC_4

The minimum full-size transverse Charpy energy is 40 ft-lb, and a DWTT 100 percent shear area at the minimum service temperature is specified. A toroidal arrestor is being considered, but the weight of any components to be lifted at one time, must be less than 150 pounds in this case.

Step 1 - Determine Fracture Speed

For a rich natural gas at relatively low temperatures, the gas will decompress into the two phase region which increases the fracture speed. Here decompression into the two phase region is from the gas side. Whereas in the liquid CO_2 case previously described, the decompression was from the liquid side into the two phase region. The evaluation of the rich gas decompression requires an equation of state computer program for isentropic expansion of the gas. The calculated decompressed pressure versus wave velocity is shown in Figure B.4.

The J-curve for this pipeline design is determined in the equations below, and shown graphically in Figure B.4.

$$P_a = \left[\left(\frac{1000\ \bar{\sigma}\ t}{3.33\ R}\right)\frac{2}{\pi}\right]\cos^{-1}\left[\exp - \left(\frac{\mathcal{R}\,380}{\bar{\sigma}^2\sqrt{Rt}}\right)\right] \qquad (B.21a)$$

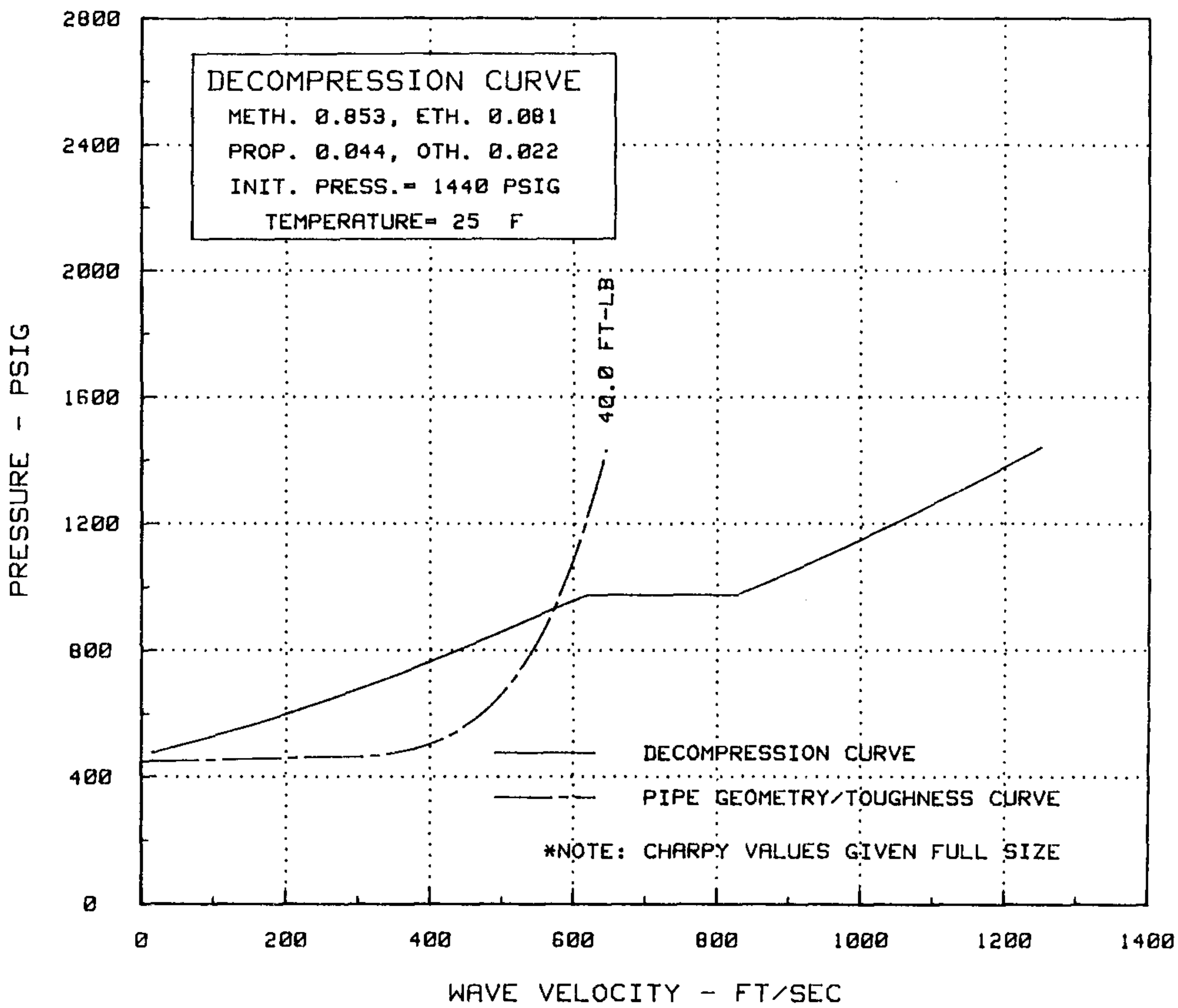

FIGURE B-4. DECOMPRESSION CURVE FOR RICH NATURAL GAS AT 25 F AND J-CURVE FOR 48-INCH-DIAMETER BY 0.738-INCH WALL X65 PIPE. (PREDICTED FRACTURE SPEED IS 575 FPS.)

$$P_a = \left[\left(\frac{(1000)(75)(.738)}{(3.33)(24)}\right)\frac{2}{\pi}\right]\cos^{-1}\left[\exp-\left(\frac{380\ (40)}{(75)^2\sqrt{(24)(.738)}}\right)\right] \tag{B.22b}$$

$$P_a = 448 \text{ psig} \tag{B.22c}$$

$$V_f = \frac{47.7\bar{\sigma}}{\sqrt{\mathcal{R}}}\left(\frac{P_d}{P_a} - 1\right)^{1/6} \tag{B.22d}$$

$$V_f = \frac{(47.7)(75)}{\sqrt{40}}\left(\frac{P_d}{448} - 1\right)^{1/6} \tag{B.22e}$$

$$V_f = 565\ \left[(P_d/448) - 1\right]^{1/6} \tag{B.22f}$$

The calculated fracture speed is 575 fps, and V_{min} is 250 fps.

Step 2 - Determine Radial Clearance

The toroidal arrestor, which will have a rock shield between the arrestors and the pipe, will be fit snugly to the pipe.

Step 3 - Determine the Equivalent Sleeve Length

Figure 21 is to be used to calculate the equivalent sleeve length and hence determine the diameter of the toroidal bars. Note this (L/D) yields the equivalent area for one bar if the bar spacing is properly selected. From Figure 21 the ratio of the equivalent sleeve length to the pipe diameter for a 575-fps fracture is 0.08.

The diameter of one of the toroidal bars is therefore,

$$d = \left(\frac{4(L/D)(D)(t)}{\pi}\right)^{1/2} \qquad \text{(B.23a)}$$

$$d = \left(\frac{4(.08)(48)(.738)}{\pi}\right)^{1/2} = 1.90 \text{ inches} \qquad \text{(B.23b)}$$

This assumes the bar stock has the same ultimate strength as the X65 pipe. Note this diameter is the minor diameter of the threaded section of the arrestor. To have an arrestor with a minor diameter of 1.90 inches the arrestor must be at least 2.25 inches if standard thread sizes are used.

One way to reduce the size of these arrestors is to make them from higher strength material. For instance if AISI 1050 steel drawn to 600 F is used its estimated minimum ultimate strength is 220 ksi and the minor diameter can be reduced by

$$d_{tor} = d \left\{\frac{\sigma_{u_{pipe}}}{\sigma_{u_{torr}}}\right\}^{1/2} \qquad \text{(B.23a)}$$

$$d_{tor} = (1.90)\left(\frac{77}{220}\right)^{1/2} = 1.125 \text{ inches} \qquad \text{(B.24b)}$$

To have an arrestor with a minor diameter of 1.125 inches the arrestor can be made from 1¼-inch bar stock.

The spacing, S, between the bars on the top of the pipe also must meet the following criteria:

$$S < (2c)(2) \qquad \text{(B.25a)}$$

or

$$S < 0.35D \qquad \text{(B.25b)}$$

whichever is less.

Equation (B.26) is used to calculate 2c, the through-wall critical crack length.(B-1)

$$\frac{12\ C_v E\pi}{A_c 8c\bar{\sigma}^2} = \ln \sec\left(\frac{\pi\ M_T\ \sigma_h}{2\bar{\sigma}}\right) \qquad \text{(B.26)}$$

C_v = Transverse Charpy V-notch energy, ft-lb.

E = Elastic modulus, psi.

A_c = Fracture area of Charpy specimen, in^2 (0.12375 in^2 for full-size specimen).

$2c$ = Total through-wall axial crack length.

$\bar{\sigma}$ = Yield strength plus 10,000 psi.

σ_h = Hoop stress at initial pressure, (PR/t), psi.

R = Pipe radius, in.

t = Pipe thickness, in.

M_T = Folias bulging factor.

$M_T = [1 + 1.255\,(c^2/Rt) - 0.0135\,(c^2/Rt)^2]^{1/2}$.

Solving Equation (B.26) by trial and error yields 2c of 7.75 inches, thus (2)(2c) is 15.5 inches. This is smaller than 0.35D (16.8 inches), thus 15.5 inches is the maximum spacing between the arrestor bars on the top of the pipe. A smaller spacing is more desirable.

Step 4 - Determine Thickness or Weight of Arrestor

The weight criterion in the design specification was that two men should not have to lift more than 150 pounds. The diameter of the toroidal bars was 2.25 inches if the bar's ultimate strength was the same as the pipe. Increasing the ultimate strength reduces the diameter and hence reduces the weight. The weight of one of the toroidal arrestor bars can be approximated by the equation below.

$$\text{Weight} = \rho^{*}_{st} \left(\frac{\pi d^2}{4}\right)\left(\frac{\pi(D+d)}{2}\right) 1.15 \tag{B.27a}$$

$$\text{Weight} = (0.281)\left(\frac{\pi d^2}{4}\right)\left(\frac{\pi(48+d)}{2}\right) 1.15 \tag{B,27b}$$

The factor 1.15 was used to compensate for the extra length of the toroidal bar past the nuts. For $d = 2.25$ inches the weight is 101.4 pounds. This is far below the 150 pound requirement. This weight requirement could be further reduced if higher strength bar stock is used. For instance, if 220 ksi ultimate strength bar stock is used, then the arrestor diameter can be reduced to 1.25 inches and the weight using Equation (B.27b) is only 30.7 pounds. The weight of one of the connector blocks using the sketch in Figure 12 is 37.8 pounds for the 2.25-inch-diameter bar, and 18.7 pounds for the 1.25-inch-diameter bar. These are sufficiently below the desired weight.

Step 5 - Toughness Specification

For the toroidal arrestor, the only necessary specification is on the round bar stock since this is the weakest link. A minimum Charpy requirement of 50 percent shear area at the minimum service temperature should be sufficient.

$^*\rho_{st}$ = density of steel $\cong$ 0.281 lb/in^3.

Step 6 - Select a Safety Margin

A safety margin could be selected in a number of different ways. One way is to assume a 50-percent safety margin on the fracture speed such that the design fracture speed is 1.5 (575 fps) or 860 fps. From Figure 21 the ratio of the equivalent sleeve length to pipe diameter is 0.146. The diameter of the toroidal arrestor bar is therefore,

$$d = \left(\frac{4(L/D)(D)(t)}{\pi}\right)^{0.5} \quad \text{(B.28a)}$$

$$d = \left(\frac{4(.146)(48)(.738)}{\pi}\right)^{0.5} = 2.56 \quad \text{(B.28b)}$$

Remember that this is the required minor diameter which means that the required arrestor diameter is 3 inches if standard threads are to be used.

The approximate weight of a bar with an ultimate strength of 77 ksi is 183 pounds. If 220 ksi ultimate strength material is used then the arrestor diameter would be 1-3/4 inches, and the approximate weight would be 60.7 pounds.